PROCEEDINGS OF SCIENCE

Gamma-ray performance of the High Energy cosmic-Radiation Detection (HERD) space mission

Giulio Lucchetta,[a,*] Luis Fariña,[a] Monong Yu,[a] Keerthana Rajan Lathika,[a] Javier Rico,[a] Laia Cardiel,[a] Joan Boix,[a] Manel Martinez,[a] Jorge Casaus,[b] Joan Mauricio,[c] David Gascón,[c] Fabio Gargano,[d] Mario Nicola Mazziotta[d] and Yong-Feng Huang[e] for the HERD collaboration

[a] *Institut de Física d'Altes Energies (IFAE) - The Barcelona Institute of Science and Technology (BIST), Bellaterra, Barcelona, Spain*

[b] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*

[c] *Institute of Cosmos Sciences - University of Barcelona (ICC-UB), Barcelona, Spain.*

[d] *Istituto Nazionale di Fisica Nucleare (INFN) - Sezione di Bari, Bari, Italy*

[e] *Nanjing University, Department of Astronomy, Nanjing, China.*

E-mail: gluchetta@ifae.es

The High Energy cosmic-Radiation Detection (HERD) facility has been proposed as one of the main scientific payloads on-board the China Space Station. HERD is expected to be installed around 2027 and to operate for at least 10 years. The major scientific goals of the mission are the study of cosmic rays' energy spectra and composition up to the PeV range, the indirect search of dark matter particles via annihilation/decay, and observation of the high-energy gamma-ray sky above $\sim 100\,\mathrm{MeV}$. To accomplish the broad scientific case, HERD is designed as a large acceptance telescope: a central 3D imaging calorimeter (CALO) is surrounded on the top and the four lateral sides by scintillating fiber tracking detectors (FIT), plastic scintillator detectors (PSD) and silicon charge detectors (SCD). In order to maximize the performance for gamma rays studies, an ultra-low-energy gamma-ray (ULEG, $E > 100\,\mathrm{MeV}$) advanced trigger system, based on the fast combination of 3-in-a-row patterns in FIT and the PSD veto, has been designed. In this work we characterize the performance of the HERD-ULEG trigger in terms of gamma-ray effective area, angular resolution and sensitivity. We also present the design, performance and optimization of the gamma-ray trigger system based on both software simulations and preliminary hardware validations.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

[*] Speaker

PoS(ICRC2023)691

1. Introduction: the HERD space mission

The High Energy cosmic-Radiation Detection (HERD) facility is scheduled to be installed on the China Space Station (CSS) around 2027, operating for at least 10 years. HERD will accomplish important and pioneering goals in different research areas, encompassing cosmic-ray (CR) observations, dark matter search and survey of the gamma-ray sky.
The core of the instrument consists of a 3D imaging CALOrimeter (CALO), surrounded on the top and the four lateral sides by the other sub-detectors: the Fiber Tracker (FIT), the Plastic Scintillator Detector (PSD) and the Silicon Charge Detector (SCD). The calorimeter is made of about 7500 LYSO[1] crystals, $3 \times 3 \times 3\,\mathrm{cm}^3$ in size, each corresponding to about 2.6 radiation lengths and 1.4 Molière radius. The scintillation light from each crystal is read-out by two independent systems, allowing for cross-calibration: the first system consists of WaveLength Shifting fibers (WLS) coupled to image Intensified scientific CMOS (IsCMOS) cameras, and to Photo-Multiplier Tubes (PMTs) for triggering, while the second system consists of photo-diodes (PD) connected to the HIDRA custom front-end electronics chips. The HERD's calorimeter permits the energy reconstruction of CRs and gamma rays and e/p discrimination. The HERD scintillating FIber Tracker (FIT), is composed of 5 sectors, covering the top and the four lateral sides of the CALO. The FIT is designed to fulfil different purposes: act as conversion material for gamma rays, reconstruct the tracks of the electrons and positrons generated in the pair production process, reconstruct the trajectories and absolute charge value of cosmic rays. In the current design, all FIT sectors consist of 7 tracking planes, each of them comprising two layers of FIT modules measuring the two orthogonal spatial coordinates. Each module includes a scintillating fiber mat, spanning the whole length of each face along alternating directions, and three silicon photomultipliers (SiPMs) at the end of the fiber mat, read-out by the custom designed Beta ASIC. The PSD, placed outside the FIT and CALO sub-detectors, is composed of two layers of staggered plastic scintillator bars. The PSD is used as an anti-coincidence detector, discriminating the incident photons from charged CRs; furthermore, it provides charge measurements for the latter. Each bar is read-out by several SiPMs; the produced signal is then processed through the Beta ASICs. The SCD, the outermost detector of HERD, is made of 8 layers of thin single-sided silicon micro-strip detectors stacked in the two orthogonal directions. The sub-system is carefully designed to perform precise measurement of the charge of the incoming CRs, from hydrogen to iron. Finally, a Transition Radiation Detector (TRD) is placed on one of the lateral sides of the instruments, providing calibration for the CALO to protons in the energy range of 1-10 TeV. Further details about the mission design and science objectives can be found in [1].
This work focuses on the gamma-ray performance of the HERD mission. HERD will operate in synergy with the LHAASO and CTA ground-based observatories, ensuring continuous observations of the high-energy gamma-ray sky from space, after the end of Fermi-LAT operational lifetime. Moreover, due to the large field-of-view ($\sim 2\,\pi$), HERD will play a key role for transient observations and in the context of multi-messenger astronomy.

[1]Lutetium–yttrium oxyorthosilicate.

2. Design of the ultra-low-energy gamma-ray trigger system (ULEG)

The baseline Low-Energy Gamma-ray (LEG) trigger, as described in [2] requires an energy deposition in the CALO and a veto signal from the PSD, in order to discriminates photons from the CRs background. The energy threshold of the baseline LEG trigger, dictated by the CALO-PMT system, is about 350-500 MeV. In order to exploit full potential for gamma-ray observations and lower the energy threshold down to at least 100 MeV an Ultra-Low-Energy Gamma-ray (ULEG) advanced trigger system has been designed. The ULEG trigger is based on a fast combination of a FIT trigger signal and the PSD veto (see Fig. 1, left). The FIT trigger signal is based on the so-called *three-in-a-row* (3IR) logic, which identifies hits in at least three consecutive FIT tracking planes, on both orthogonal tracking directions, compatible with the electron-positron tracks produced by pair conversion of gamma rays. In the current ULEG design a maximum shifting of one fiber mat (ΔM = 1) between two consecutive tracking planes is allowed, leading to the patterns illustrated in Fig. 1, right.

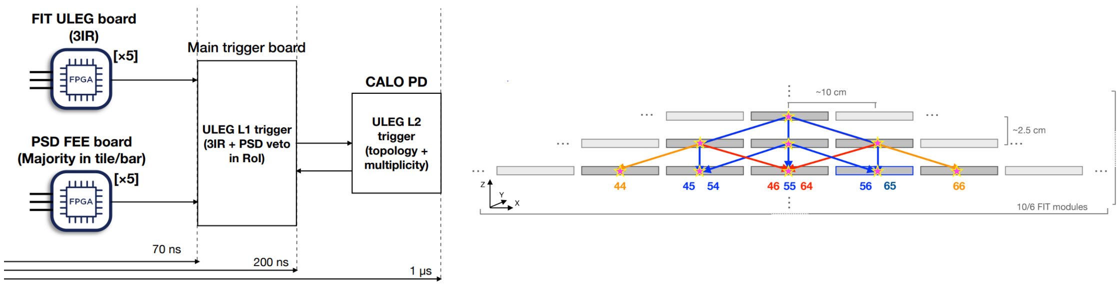

Figure 1: Left: schematic representation of the ULEG trigger concept. Right: illustration of all the patterns starting in a given FIT mat, compatible with the current definition of the 3IR logic.

All the 3IR compatible patterns provided by the read-out of the FIT mats through the Beta ASICs, are identified at level-0 (L0) and combined to the veto signal from the PSD at the level-1 (L1) trigger. To reduce the threshold noise level, while maintaining a high selection efficiency for gamma rays, we confine the search for the PSD veto signal within a region of interest (RoI). This RoI is defined by the projection into the PSD of all trajectories compatible with the 3IR pattern. Information about the energy deposition in the CALO from the PD system are finally combined at the level-2 (L2), in order to reduce the total ULEG trigger rate to a level acceptable for the read-out.
The performance of the ULEG trigger system is evaluated with the HerdSoftware package. Based on the definition of our *target gamma-ray sample*, which comprises gamma rays with energies from 10 MeV to 100 GeV, converting inside the FIT volume, producing hits in at least three FIT tracking planes, and releasing at least 50% of the energy in the CALO, we have demonstrated that an efficiency of ~ 99% is reached for the implemented 3IR-ΔM = 1 design.

3. Performance of the ULEG trigger system for gamma-ray astronomy

The gamma-ray performance of HERD-ULEG system has been evaluated in terms of effective area, angular resolution, and sensitivity for the target gamma-ray sample. The effective area (A_{eff}) is computed, as a function of the photon energy and direction, as the product of the generation area of the simulation and the detection efficiency, expressed by the ratio of triggered to generated events:

$$A_{\text{eff}}(E_\gamma, \theta, \varphi) = A_{\text{gen}}(E_\gamma, \theta, \varphi) \cdot \frac{N_{\text{trigger}}(E_\gamma, \theta, \varphi)}{N_{\text{gen}}(E_\gamma, \theta, \varphi)} \,. \tag{1}$$

The HERD-ULEG effective area as a function of the energy is reported in Fig. 2, left. Since the HERD tracker does not include high-density conversion layers, the effective area is drastically reduced compared to an instrument like *Fermi*-LAT, down to a factor of ten. On the other hand, the wide field-of-view, achieved via the instrumentation of the five sectors, partly compensate for the small detection efficiency, as can be seen by the acceptance plotted in Fig. 2, right.

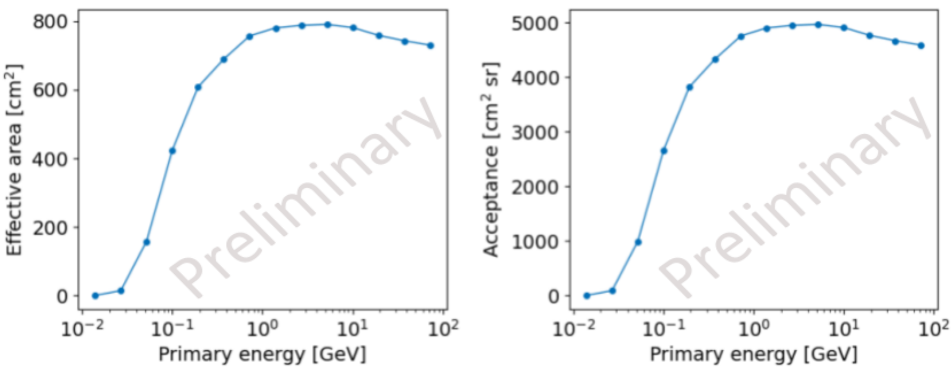

Figure 2: Effective area (left) and acceptance (right) for the HERD-ULEG system, as a function of the gamma-ray energy.

Given the CSS orbit, HERD's orientation and lifetime, and given the extragalactic and galactic gamma-ray background fluxes as measured by *Fermi*-LAT[2], HERD exposure to gamma rays can be computed (see Fig. 3). An overall average rate of ∼ 0.01 counts/s has been computed for diffuse gamma rays.

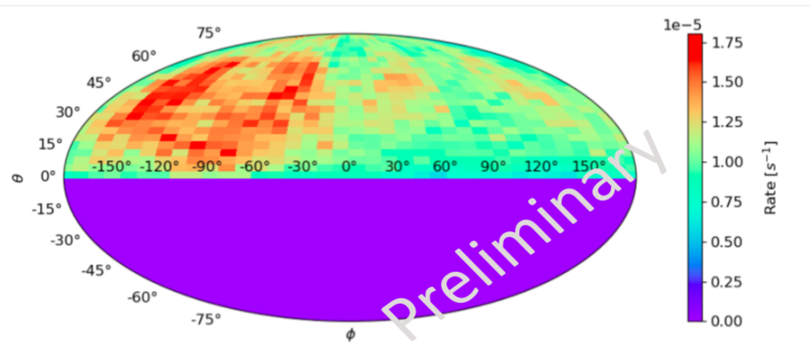

Figure 3: Map of the yearly averaged gamma-ray receiving rate in HERD's local coordinate system. ϕ is the azimuth angle, with $\phi = 0°$ indicating the forward moving direction of the CSS. The angle θ identifies the particle direction, where $\theta = 90°$ indicates a particle coming from zenith.

A beneficial effect of the exclusion of high-Z conversion foils is the minimization of multiple scattering inside the tracker, which results in an improvement of the angular resolution of the

[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html.

instrument. As a preliminary proxy method for the determination of the angular resolution, the hit pairs in both orthogonal direction of the FIT mats are identified and their position is smeared accordingly to the spatial resolution given by the FIT fibers and read-out (250 μm). The tracks for e^+ and e^- are then fitted to these points, and the direction of the incoming gamma ray is reconstructed. The point spread function (PSF) of the instrument is then defined as the 68% containment angle between the reconstructed and the true tracks. HERD's PSF for the top and one lateral sector is compared to *Fermi*-LAT's one in Fig. 4, left. A pair tracking algorithm based on Kalman filter is currently under development. Finally, the differential sensitivity for point-like sources is presented in Fig. 4, right, for a 5 σ detection, and for different locations and exposure times.

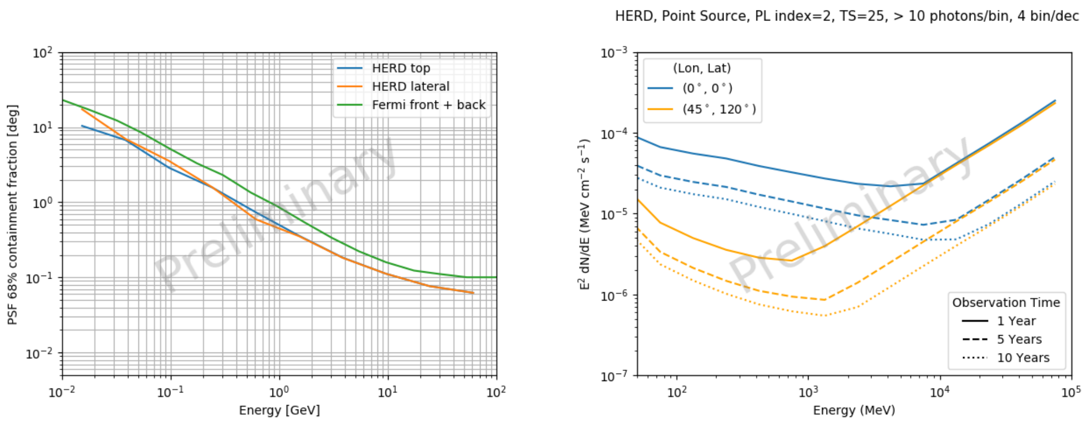

Figure 4: Left: HERD's PSF for the top and lateral sectors, compared to *Fermi*-LAT's one. Right: HERD's differential sensitivity for point-like sources, based on the pair tracking in FIT.

4. Acceptance and rates of the ULEG system for CR background

In order to characterize properly the occupancy level for the FIT and PSD electronics and compute rates at each level (L0, L1 and L2) of the ULEG trigger a dependable model for the CR flux is required. At energies below 10-20 GeV CRs are affected by the solar modulation and the Earth's magnetic field. The CR flux changes within the 11-year solar cycle, exhibiting an anti-correlation. Moreover, due to Earth's magnetic field configurations, the CR flux is strongly modulated, depending greatly on the reached geomagnetic latitudes (λ), and so, on the altitude and the inclination of the mission. The modulation effect is maximum on the equator and minimum at the poles; for each geomagnetic latitude it exist a critical rigidity (rigidity cutoff) below which CRs cannot reach the Earth. The interaction of CRs with target nuclei in the Earth's atmosphere also results in the production of a secondary component observed under the cutoff, mainly constituted of electrons, positrons and protons. A model for the CR flux has been developed based on measurements from AMS-01 [3], PAMELA [4, 5], NINA-2 [6], MARYA-2 [7] and HEPD-Limadou [8]. An example of the proton and electron CR flux for the highest geomagnetic latitudes spanned by HERD ($\lambda \lesssim 1.0$ rad) can be found in Fig. 5. Based on this background model, the maximum count rates per unit area for the FIT and the PSD detectors are respectively 3.5 counts/(s cm^2) and 5.2 counts/(s cm^2).

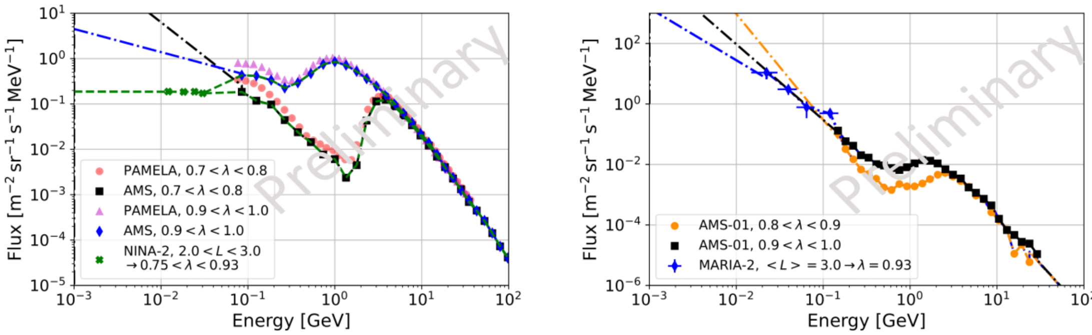

Figure 5: Proton (left) and electron (right) CR flux at high geomagnetic latitudes.

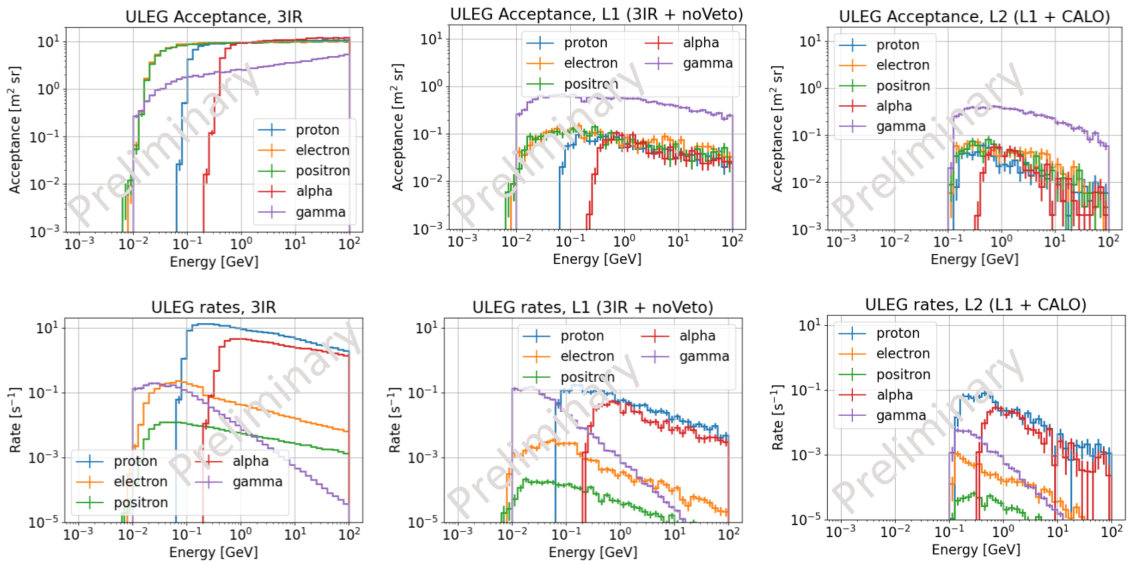

Figure 6: Acceptance (top) and rates (bottom) for protons, electrons, positrons and helium at high geomagnetic latitudes, and for all trigger levels (3IR-L0, L1 and L2, from left to right). The extragalactic gamma-ray background rate is also shown for comparison.

By convolving the CR flux with the acceptance for protons, helium, electrons and positrons (Fig. 6, top), the total rates for the ULEG trigger can be computed at each level(Fig. 6, bottom)[3]. The overall rate for the 3IR-L0 level is $\sim 2.7 \times 10^4$ counts/s, dropping down to $\sim$ 198 counts/s at L1 and $\sim$ 56 counts/s at L2, considering a threshold of 100 MeV for the CALO-PD system. Most of the remaining count rate measured at L1 and L2 is due to gaps between PSD bars and between PSD sectors in the current version of the HERD geometry, as it can be deduced from the hotspots in Fig. 7. Current efforts to improve the PSD hermeticity are underway.

Another source of background is due to the so-called irreducible background: cosmic rays interacting with the SCD and passive material of the payload can produce photons through neutral pions decay, bremsstrahlung or positron-electron annihilation. When passing the PSD, the photons produced by these interactions are indistinguishable from the signal that a gamma-ray telescope

[3]The contribution of nuclei heavier than helium is negligible.

aims to measure. In order to study this background component a fully hermetic PSD is considered in our simulations. The irreducible background for the TOP sector, for high and low geomagnetic latitudes, compared to the extragalactic and galactic gamma-ray background components, is shown in Fig. 8. As it can be observed the irreducible background is a sizable background component for HERD; at high geomagnetic latitudes, considering a 100 MeV energy deposition in the CALO, a total rate of 0.17 counts/s for all five sectors has been computed.

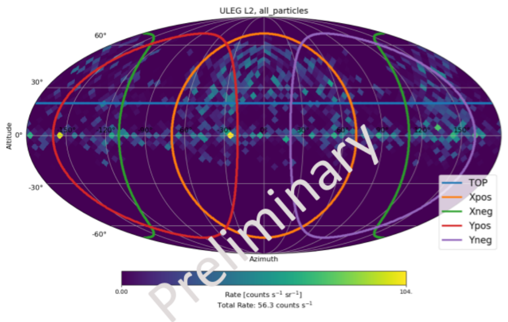

Figure 7: Total cosmic-ray rate for the ULEG-L2 trigger in sky coordinates. The portion of the sky seen by each HERD sector is also shown.

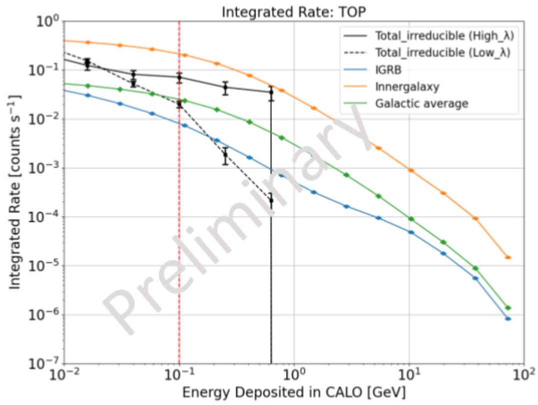

Figure 8: Contribution of the irreducible background compared to galactic and extragalactic gamma-ray background.

5. Hardware implementation of the ULEG trigger

To demonstrate the ULEG trigger proof-of-concept, a Xilinx EK-Z7-ZC706-G evaluation board is currently being used. The board communicates, configures and reads-out the Beta ASICs, and generates the trigger signals for ULEG: the 3IR trigger signal from the FIT and the veto signal from the PSD, based on the combination of the majority of trigger signals in the bars and regions of interest. These trigger signals are sent to a main trigger board where they are combined to the CALO trigger at L2. Hardware validation of the ULEG trigger is foreseen in two beam tests at CERN in fall 2023 with prototype detectors for FIT and PSD: a PS beam test with protons in September 2023, and a SPS beam test with ions in October 2023.

6. Conclusions

We presented the design and performance of the Ultra-Low Energy Gamma-ray (ULEG) trigger system for the HERD space mission, aimed to maximize capabilities for gamma-ray studies at energies $E \gtrsim 100$ MeV. The gamma-ray performance of the HERD-ULEG system was assessed in terms of effective area, acceptance, angular resolution, and sensitivity. The expected data rates for cosmic-ray and gamma-ray background sources have been computed. The hardware validation of the ULEG system is foreseen in two beam tests at CERN in fall 2023.

Figure 9: Picture of the Xilinx EK-Z7-ZC706-G evaluation board configuring and controlling a Beta mezzanine hosting four Beta ASICs.

7. Acknowledgment

This study was supported by MICIIN (project reference: PID2020-116075GB-C2; AEI/10.13039/501100011033), the European Union NextGenerationEU (PRTR-C17.I1) and the Generalitat de Catalunya.

References

[1] Shuang-Nan Zhang for the HERD collaboration, *Introduction of the HERD space mission*, Proceedings of the 38th International Cosmic Ray Conference (ICRC2023), Nagoya (Japan), 2023.

[2] Qi Wu et al. for the HERD collaboration, *Status of the HERD trigger design*, Proceedings of the 38th International Cosmic Ray Conference (ICRC2023), Nagoya (Japan), 2023.

[3] M. Aguilar et al., *The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part I – results from the test flight on the space shuttle*, Physics Reports 366, 2002.

[4] O. Adriani et al., *Reentrant albedo proton fluxes measured by the PAMELA experiment*, Journal of Geophysical Research (Space Physics) 120, 2015.

[5] O. Adriani et al., *Measurements of quasi-trapped electron and positron fluxes with PAMELA*, J. Geophys. Res. 114, 2009.

[6] V. Bidoli et al., *Energy spectrum of secondary protons above the atmosphere measured by the instruments NINA and NINA-2*, Annales Geophysicae 20, 2002.

[7] V. Mikhailov, *Low energy electron and positron spectra in the earth orbit measured by MARIA-2 instrument*, International Journal of Modern Physics A 17, 2002.

[8] Alessandro Sotgiu, *Measurement of the re-entrant lepton spectrum with the High-Energy Particle Detector on board CSES-01*, Proceedings of 37th International Cosmic Ray Conference (ICRC2021), 2021.